PAPER NO. 67

LONG TERM FIELD STUDY INTO THE DURABILITY OF SILICA FUME CONCRETE IN A MARINE TIDAL ZONE

B Sealey, O Skjølsvold, C Goodier, H Justnes

ABSTRACT

In 1983, samples of reinforced concrete made from a range of concrete mixtures containing varying amounts of CEM I and silica fume were placed in a marine tidal zone at Trondheim, Norway. Examination and testing of the samples occurred periodically during the initial 21.5 years of exposure.

In 2014, after 31 years exposure, the field site closed and the samples examined for a final time. This paper presents the results of compressive strength, electrical resistivity and chloride ingress tests on cores taken from the 31-year-old samples.

The durability performance of the silica fume mixtures was seen to be significantly better than the CEM I mixtures. The uniqueness of this research is being able to draw upon 31 years of empirical real-world data.

Key words: Durability, silica fume, chloride ingress, tidal zone

INTRODUCTION

A long-term study began in 1982, to investigate the durability of concrete sited in a marine tidal zone. Samples cast in October 1982, comprising 0.5m by 1.5m by 1.5m concrete blocks, were installed in March 1983 at Trondheim, on the Norwegian coast. Five concrete mixtures were involved, with the aim of comparing the long-term durability of conventional concrete with that of ‘higher performance’ concrete made using silica fume.

Table 1 shows the mixtures used to make the sample blocks. Mix 1 being a typical C35 mix, designed according to common practice in Norway in the early 1980s, using Portland cement equivalent to CEM I [1] and lignosulfonate type plasticiser. To investigate the effect of silica fume, Mixes 2, 3, 4 and 5 have silica fume added at different dosages (10 and 20% by mass of Portland cement), in combination with various cement contents and water/cement ratios.

Silica fume, also known as microsilica, originates as a co-product from the production of silicon or ferrosilicon. Key characteristics of silica fume are:

- Pozzolanic – it consumes calcium hydroxide and reacts with alkalis in the concrete. This leads to less alkali in the pore solution and less calcium hydroxide in the matrix. Consequently, more calcium silicate hydrate binder is present and less calcium hydroxide

- High purity – compared to other pozzolans, silica fume has a relatively high SiO_2 content

- Small particles (typically 0.1 to 0.3 µm) and high specific surface area – helps improve particle packing and cohesion in the concrete mixture

Table 1 - Concrete Mix Designs

	Control	Reduced cement + Silica fume		Increased cement + Silica fume	
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
CEM I, kg/m^3	370	275	234	457	394
w/c ratio	0.54	0.70	0.83	0.45	0.55
Silica fume dosage*	0 %	10 %	20 %	10 %	20 %
Silica fume, kg/m^3	0	27.5	46.8	45.7	78.8
Total binder, kg/m^3	370	302.5	280.8	502.7	472.8
w/(total binder) ratio	0.54	0.63	0.69	0.41	0.46

* calculated as percent of CEM I mass

The blocks were placed in the coastal tidal zone at Trondheim, Norway. Table 2 shows indicative climate data for the site [2]. Normal tidal range in the Trondheim area is 1.83m. At normal low tide, the blocks were not immersed in seawater. However, a splash zone condition frequently prevailed, due to wind and wave action. At normal high tide, approximately 0.2m of the blocks remained above water. Frost episodes occurred during winter.

Table 2 – Average climate data at test site [2]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temp, °C	-2.5	-1.8	0.8	4.0	9.6	12.8	14.0	13.6	9.8	6.2	1.3	-1.0
Sea temp, °C	4.3	3.3	4.3	5.6	9.1	12.1	13.9	13.8	11.6	9.2	6.7	5.3
Saline content, %	3.18	3.18	3.24	3.13	2.27	2.22	2.32	2.62	2.90	3.06	3.03	3.08

After installation, the blocks were assessed at age 1.5, 5, 9, 14 and 21.5 years [2]. Finally, in 2014, the research site closed and the blocks removed. Presented in this paper are a selection of results from tests carried out on the blocks at the time of their removal in 2014, i.e. after 31 years of exposure in a tidal zone. The authors will publish more results and analysis subsequently.

RESULTS – ASSESSMENT OF BLOCKS AFTER 31 YEARS IN TIDAL ZONE

Visual inspection

Table 3 - Visual inspection

Control	Reduced cement + Silica fume		Increased cement + Silica fume	
Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Severe spalling on upper parts of the blocks, especially corners	Moderate spalling at upper corners	Moderate spalling at upper corners	Insignificant spalling at corners	Insignificant spalling at corners
Severe surface cracking due to freeze/thaw and/or alkali silica reactions	Some exposed aggregates at the surface, i.e. the surface paste layer is removed	Some exposed aggregates at the surface	Some exposed aggregates at the surface	Some exposed aggregates at the surface
Generally in poor condition				

Figure 1 - Sample block, Mix 1

Figure 2 - Sample block, Mix 4

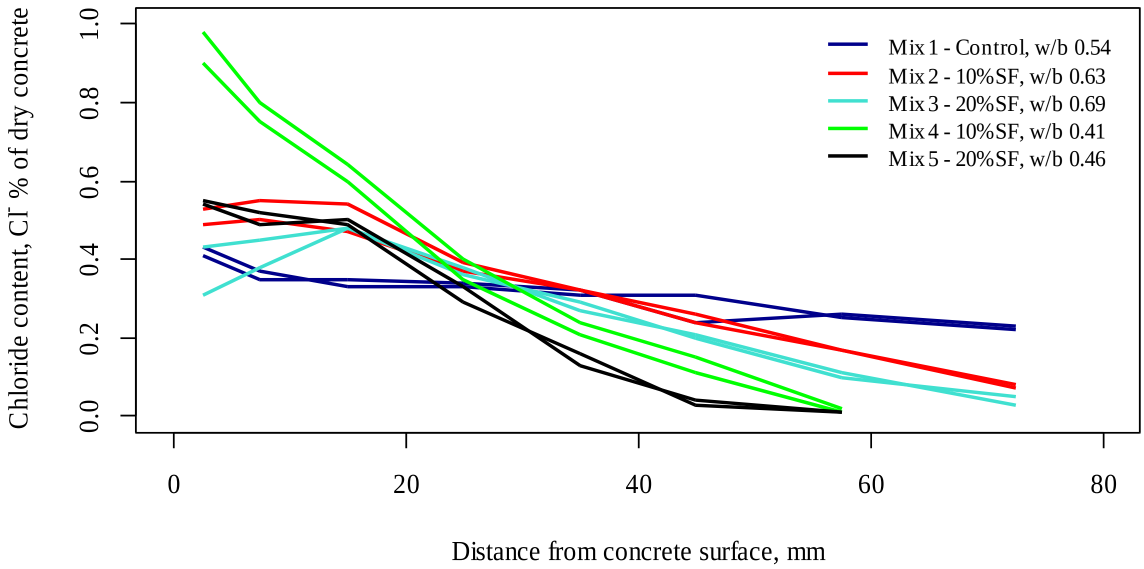
Chloride ingress

The chloride ingress profile was determined for specimens from drilled cores. Thin layers (5 to 15 mm) were ground from the surface and the chloride content for each layer determined. Table 4 and Figure 3 show the results.

Table 4 - Chloride ingress, % Cl^- of dry concrete at layer distance from the surface

	Control		Reduced cement + Silica fume				Increased cement + Silica fume			
	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
	a	b	a	b	a	b	a	b	a	b
0-5mm	0.41	0.43	0.53	0.49	0.43	0.31	0.9	0.98	0.55	0.54
5-10mm	0.35	0.37	0.55	0.5	0.45	0.38	0.75	0.8	0.52	0.49
10-20mm	0.35	0.33	0.54	0.47	0.48	0.48	0.6	0.64	0.49	0.5
20-30mm	0.34	0.33	0.39	0.37	0.38	0.36	0.35	0.4	0.29	0.33
30-40mm	0.32	0.31	0.32	0.32	0.27	0.29	0.21	0.24	0.16	0.13
40-50mm	0.24	0.31	0.26	0.24	0.21	0.2	0.11	0.15	0.03	0.04
50-65mm	0.26	0.25	0.17	0.17	0.11	0.1	0.01	0.02	0.01	0.01
65-80mm	0.23	0.22	0.07	0.08	0.03	0.05	-	-	-	-

Figure 3 - Chloride ingress profiles



Compressive strength

The compressive strength was determined from drilled cores – tested according to EN 12390-3 [3] after 3 days submersion in water at 20°C. The end surfaces were ground before testing.

Table 5 – Compressive strength results

	Control		Reduced cement + Silica fume				Increased cement + Silica fume			
	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
	a	b	a	b	a	b	a	b	a	b
Strength*, MPa	34.3	31.3	39.6	40.8	44.5	45.6	61.6	55.1	58.3	53.9
Mean str.*, MPa	32.8		40.2		45.1		58.4		56.1	
Original strength, lab cylinder @ 28 day (in 1982)	34.0		35.2		33.4		54.0		49.0	

*Recalculated according to NS 3465:2003 [4], compressive strength for cylinder with height/diameter-ratio 2.0

Electrical resistivity

Electrical resistivity was measured on specimens with height approximately 100mm, derived from cores drilled from both the outer and inner parts of the blocks. Testing was performed at 20°C after 1 day submersion in water after drilling. The end surfaces were ground and tested according to SINTEF procedure KS 14-05-04 524 [5].

Table 6 - Electrical resistivity results

	Control		Reduced cement + Silica fume				Increased cement + Silica fume			
	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
	a	b	a	b	a	b	a	b	a	b
Outer part, Ωm	34.6	42.2	171.4	187.0	198.2	197.2	220.0	234.7	373.6	357.6
Mean	38.4		179.2		197.7		227.4		365.6	
Inner part, Ωm	c	d	c	d	c	d	c	d	c	d
	32.4	33.3	154.9	148.2	199.7	204.4	121.6	120.9	209.9	208.5
Mean	32.7		151.6		202.1		121.3		209.2	

DISCUSSION

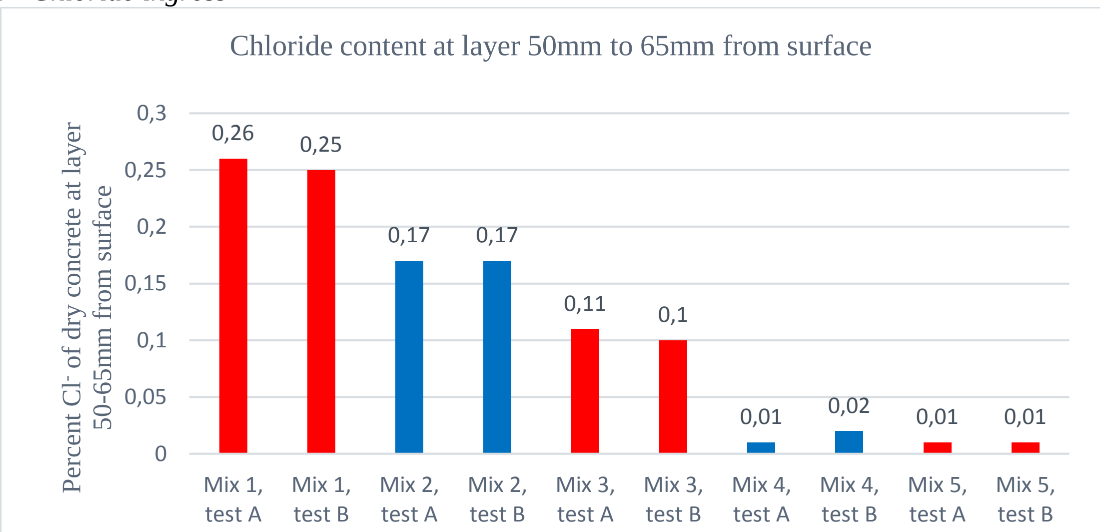
Designed in 1982, the concrete mixtures used for this long-term study no longer reflect current practices. For example, no samples contain a ‘triple-blend’ of Portland cement blended with silica fume + either fly ash or ground granulated blast furnace slag. Nevertheless, despite these limitations there is value in the results because of the long duration of in-situ sample exposure.

On visual inspection, Mix 1 (control mix; non-silica fume) was found to be in a generally poor condition (Table 3; Figure 1). Severe spalling and severe surface cracking was apparent; it is likely this is due to alkali silica reactions and possibly also freeze-thaw. This is in contrast to the good condition of Mixes 4 and 5 (silica fume added; reduced water/binder ratio) – Mix 4 can be seen in Figure 2. Note that a structural analysis (including thin section analysis) of samples from the five blocks has been undertaken and the results are to be published subsequently.

A primary concern when specifying concrete for marine concrete is reinforcement corrosion caused by the penetration of chlorides to the level of the reinforcement.

Chloride content results for the samples after 31 years of exposure (Table 4; Figure 3) show that the addition of silica fume has reduced chloride content significantly at typical reinforcement depths. Figure 4 highlights chloride content at 50mm to 65mm depth – Mixes 4 & 5 both have chloride content below what would normally be expected to cause corrosion. It is also interesting to note that Mixes 2 & 3 (both with silica fume) show reduced chloride ingress compared to the non-silica fume Mix 1, despite Mix 1 having a lower water/binder ratio. The results are a consequence of an improved, more homogeneous, pore system in silica fume concrete, giving reduced permeability. It is likely that cracks occurring in the concrete will also have influenced the chloride profiles.

Figure 4 - Chloride ingress



It is well documented that silica fume causes a significant reduction in electrical conductivity of concrete [6, 7]. Electrical resistivity results for the 31 year old samples, summarised in Table 6, confirm a significant improvement with silica fume addition, compared to the non-silica fume control (Mix 1). The addition of silica fume will therefore be beneficial for durability because active corrosion (of steel within the concrete) is an electrochemical process, governed by the resistivity of the concrete.

CONCLUSION

- This 31 year field study has provided valuable empirical data

- Durability performance of the silica fume concrete mixtures was seen to be significantly better than a non-silica fume control mix; structural integrity of the silica fume concrete with reduced water/binder ratio was maintained

- Silica fume mixes showed significant reductions in chloride contents at typical reinforcement depths

- Electrical resistivity of the concrete mixtures containing silica fume was substantially increased

- The practical consequence of these factors is that silica fume significantly reduces the risk of chloride-initiated corrosion, especially in concrete exposed to severe environments

- These results are consistent with the many previous studies that show silica fume concrete to be more resistant than conventional concretes to degradation caused by the ingress of aggressive ions; this is the first time however, that this has been demonstrated empirically over a 31 year time span

REFERENCES

1. BS EN 197-1:2011, ‘Cement. Composition, specifications and conformity criteria for common cements’, ISBN 978 0 580 91964 0
2. Skjølsvold, O., Justnes, H., Hammer, T.A., and Fidjestøl, P., (2007) “Long-Term Chloride Intrusion in Field Exposed Concrete with and without Silica Fume” 9th CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Warszawa, Poland, Vol ACI SP 242-16, p199-209.
3. BS EN 12390-3:2009, ‘Testing hardened concrete. Compressive strength of test specimens’, ISBN 978 0 580 76658 9
4. NS 3465:2003, ‘Execution of concrete structures - Common rules’, Standards Norway [In Norwegian]
5. Procedure KS 14-05-04 524, SINTEF, Trondheim, Norway
6. ACI Report 234R-06: Guide for the Use of Silica Fume in Concrete (Reapproved 2012), ISBN 9780870312144
7. Goodier, C.I., Xueting, C., Christodoulou, C., Dunne, D., and Yea, R. (2015), Resistivity and Water Absorption of Concrete, 4th Int. Conf. on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Leipzig, 05–07/10/15, ISBN 1315677644, 9781315677644, CRC Press, Eds Dehn, F., Beushausen, H.D., Alexander, M.G., and Moyo, P.,